MODULE 5.0: HISTORICAL ACCIDENTS

Introduction

Welcome to Module 5.0 of the Nuclear Criticality Safety for Directed Self-Study Course! This is the fifth of five modules in this directed self-study course. The purpose of this module is to assist you by providing an historical look at nuclear criticality accidents.

This directed self-study module is designed to assist you in accomplishing the learning objectives listed at the beginning of the module. The module has self-check questions and activities to help you assess your understanding of the concepts presented in the module.

Before You Begin

It is recommended that you have access to the following material:

- ☐ Trainee Guide

Complete the following prerequisite:

- ☐ Module 4.0 Nuclear Criticality Safety Controls

How to Complete this Module

1. Review the learning objectives.
2. Read each section within the module in sequential order.
3. Complete the self-check questions and activities within this module.
4. Check off the tracking form as you complete the self-check questions and/or activity within the module.
5. Contact your administrator as prompted for a progress review meeting.
6. Contact your administrator as prompted for any additional materials and/or specific assignments.
7. Complete all assignments related to this module. If no other materials or assignments are given to you by your administrator, you have completed this module.
8. Ensure that you and your administrator have dated and initialed your progress on the tracking form.
9. Go to the Trainee Guide and review the steps for course completion.

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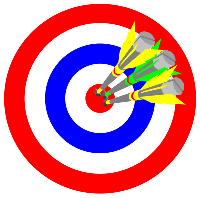
Learning Objectives



5.1 Upon completion of this module, you will be able to identify lessons learned from previous nuclear criticality accidents, as well as causes and termination mechanisms of the accidents.

5.1.1 Identify the causes and termination mechanisms of selected nuclear criticality accidents.

5.1.2 List the similarities of the selected nuclear criticality accidents.

5.1.3 Identify lessons learned through nuclear criticality accident histories.

5.1.4 Given a scenario, identify similarities to previous nuclear criticality accidents.

Y-12 CHEMICAL PROCESSING PLANT, OAK RIDGE, TENNESSEE; JUNE 16, 1958

Background

On June 16, 1958, the first known process plant nuclear criticality accident occurred during an enriched uranium recovery operation at the Y-12 Plant in Oak Ridge, Tennessee.

The nuclear criticality accident occurred in Building 9212, C-1 Wing, in a processing area.

In the past, two approaches to nuclear criticality safety had been used at Y-12. First, operations personnel and their supervisors sometimes relied on administrative controls to prevent nuclear criticality accidents. Sometimes they relied on the geometric design of equipment to prevent accidental nuclear criticality.

At the time of the nuclear criticality accident, Y-12 was changing from a policy of administrative control practices to a policy of geometric control practices in uranium recovery operations. B-1 Wing of Building 9212 was being redesigned to allow all processing to be done, from start to finish, without transfer from favorable geometry equipment. This redesign would greatly reduce the chance for human error in B-1 Wing; however, high concentrations of uranium were present at a number of points in the B-1 Wing equipment. Because of this, there remained a high probability for a nuclear criticality accident if solutions collected in an unfavorable geometry container. Therefore, unfavorable geometry containers (such as waste baskets, mop buckets, desk drawers, and tool boxes) were not allowed in the process area of B-1 Wing.

In C-1 Wing of Building 9212, both administrative controls and some physical geometry control were used for nuclear criticality safety. Rigid administrative controls (batching procedures, duplication of measurements/analyses) were required because unfavorable geometry containers were still used; however, solutions were routinely dilute and/or uranium quantities kept small so that the unfavorable geometry containers did not represent a significant problem.

At the time of the nuclear criticality accident, sections of B-1 Wing were not yet ready for operation, so a temporary transfer pipeline was installed from B-1 Wing to C-1 Wing. Under this temporary arrangement, B-1 Wing produced the uranyl nitrate and C-1 Wing received the solution. Thus, the concentration of solution in C-1 Wing could be the same as the concentration of solution in B-1 Wing.

Responsibility for operation of the transfer pipeline was divided among three different supervisors, located in three physically separated areas, which made communication difficult.

While the recovery system was being remodeled, the areas were also in the midst of an inventory. The inventory involved different enrichments and concentrations of uranium solutions and required disassembly, cleaning, and reassembly of the favorable geometry tanks. Reassembled tanks were prone to leak when placed back in service, so leak testing of these tanks was performed.

Leak tests were conducted by filling the tanks with water, then checking and draining before returning them to operation. Leak testing was a routine duty performed under the supervision of the process foreman. This operation was performed without any standard operating procedures.

Normally, the B-1 Wing and C-1 Wing recovery areas would be started up at the same time after an inventory. This time, however, the equipment in B-1 Wing was ready for production before C-1 Wing was ready to receive solution. Since B-1 Wing had adequate storage facilities for solution, it was placed in operation before C-1 Wing in an attempt to minimize equipment downtime.

The Accident

Concentrated enriched uranyl nitrate solution was produced in B-1 Wing on the midnight shift before the nuclear criticality accident.

A single control valve (Valve No. 1) isolated the process equipment of B-1 Wing from storage tanks in C-1 Wing. This control valve was located in C-1 Wing and was controlled by the C-1 Wing process foremen.

Uranyl nitrate solution started leaking at a low rate through the control valve (Valve No. 1) from B-1 Wing into C-1 Wing during the morning of June 16, 1958. (See Figure 5-1.)

Workers in C-1 Wing closed Valve No. 2 immediately upstream from where the leaking solution was observed.

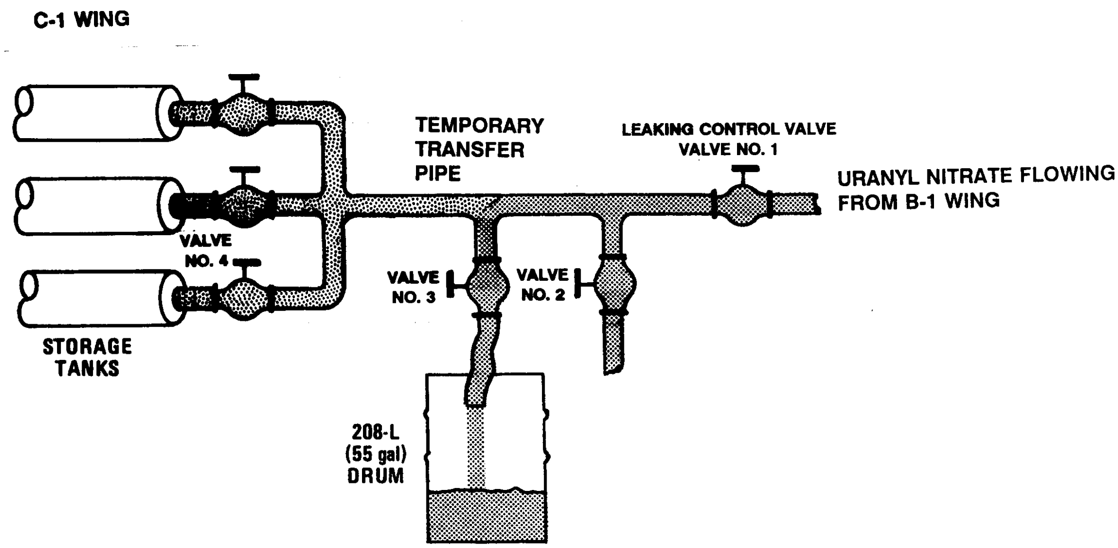
There is conflicting testimony as to whether the information concerning the leakage was passed on to day shift supervision. Regardless, no entry was made in the operating log concerning the leakage.

Closure of Valve No. 2 allowed the leaking uranyl nitrate to flow into a C-1 Wing favorable geometry storage tank and associated piping.

Later in the morning, another supervisor came on duty and assigned two operators the task of completing the leak testing of the favorable geometry tanks in C-1 Wing. Workers partially filled these favorable geometry storage tanks with water.

To ensure uranyl nitrate was not flowing from B-1 Wing into the tanks to be tested in C-1 Wing, an operator was asked to check the control valve (Valve No. 1) in the line from B-1 to C-1. The operator reported finding the valve closed.

Figure 5-1. 1958 - Y-12, Geometrically Favorable Storage Pipes Draining into Drum



GEOMETRICALLY FAVORABLE STORAGE PIPES DRAINING INTO DRUM AS SEEN IN THE Y–12 CRITICALITY ACCIDENT, 1958

No one ever checked to ensure that uranyl nitrate had not already flowed into the favorable geometry tanks in C-1 Wing.

After opening Valves No. 3 and No. 4 to drain leak-test water from a tank in C-1 into a 55-gallon drum, the operator observed a slow flow of yellow liquid into the 55-gallon drum. The operator was very familiar with the yellow color of concentrated uranyl nitrate, but he did not shut off the flow of solution.

Approximately 15 minutes later, the liquid in the 55-gallon drum reached the level at which it became critical and a blue flash was observed by personnel in the area.

The nuclear criticality alarm sounded, and all personnel immediately evacuated the area.

The solution became critical several times after the initial burst. None of the bursts caused the contents of the drum to splash out or to evaporate.

The reaction stopped approximately 20 minutes later when the solution became sufficiently dilute from leak-test water flowing into the drum.

The solution in the drum where the nuclear criticality took place was poisoned later that day by putting a sheet of rolled-up cadmium into the drum. The contents of the drum were transferred to favorable geometry storage two days later.

Result

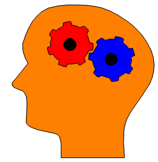
Eight Y-12 employees were in the vicinity of the drum at the time of the nuclear criticality accident. Three of these employees received radiation doses between 23 and 70 rad. They were allowed to resume their normal activities. The five remaining employees received radiation doses between 235 and 365 rad. (Personnel status as of 1997 is provided in Table 5-1.)

It must be emphasized that all of these employees heeded the alarm and instantly evacuated the area. Fatalities in this nuclear criticality accident were prevented by the rapid exit of the employees, because the recurrent (additional) bursts would have added a delayed dose to the dose received from the first burst.

Table 5-1. Personnel Histories from Y-12 Nuclear Criticality Accident of 1958

Employee	Age in 1958	Occupation	REM (RAD)	Status as of 1997
A	40	Process Operator	461 (365)	Early retirement at age 65, died 1996 at age 78
B	32	Electrician	341 (270)	Retirement at age 62, still living at age 71
C	39	Maintenance Mechanic	428 (365)	Died of lung cancer at age 54. 12 years as coal miner. Pack-a-day smoker.
D	51	Electrician	413 (339)	Died of complications from cancer at age 80
E	35	Maintenance Mechanic	298 (236)	Retired at age 62, still living at age 74
F	41	Welder	87 (68.5)	Medical treatment due to chronic obstructive pulmonary disease at age 59. Died at age 70 of heart attack, after previously diagnosed with cancer.
G	56	Maintenance Mechanic	87 (68.5)	Retired at age 62, fatal stroke at age 74
H	25	Process Operator	29 (22.8)	Other employment (TVA) at age 32, still living at age 64

Activity 1 - Y-12 Chemical Processing Plant



Purpose: To identify the causes and termination mechanisms of the Y-12 (1958) nuclear criticality accident**.**

Directions: Complete the questions. Answers are located in the answer key section of the Trainee Guide.

1. What were the events leading to this nuclear criticality accident?

2. What control factors are implied in this nuclear criticality accident?

3. What control factors were compromised and why?

4. What control factors shut down the nuclear criticality accident?

5. What preventative measures and/or lessons learned have occurred as a result of this nuclear criticality accident?

You have completed this section.
Please check off your progress on the tracking form.
Go to the next section.

LOS ALAMOS SCIENTIFIC LABORATORY; DECEMBER 30, 1958

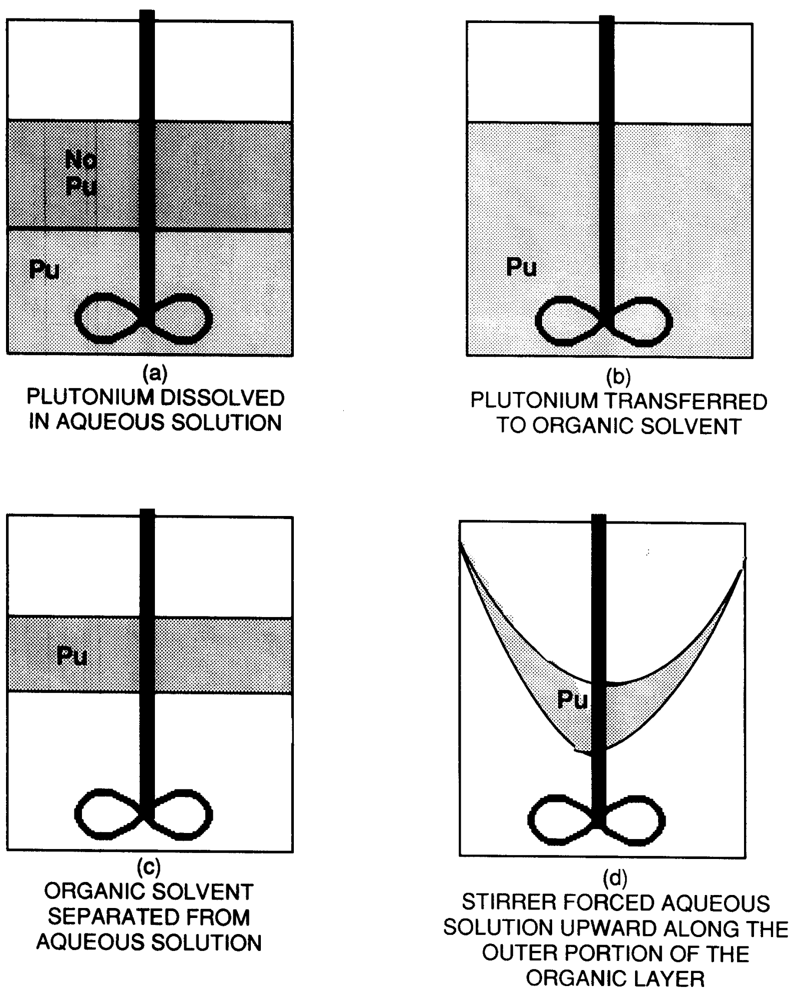
Background

The second U.S. process criticality accident occurred in New Mexico at the Los Alamos Scientific Laboratory on December 30, 1958. The process involved chemical recovery of plutonium from scrap materials containing small amounts of plutonium. Low concentrations of plutonium were typical and were expected during this operation.

There is much uncertainty as to the course of events, and there are differing accounts. An annual inventory was in progress at the time of the nuclear criticality accident. Movement of material into the area was interrupted so that residual materials in all process vessels could be checked for plutonium content. Standard operating practice required that each vessel containing plutonium be emptied and cleaned separately. The liquid used for cleaning the tanks was usually an acidic water (aqueous) solvent. After the plutonium was dissolved in the aqueous solution, the solution would then be mixed with an organic solvent (somewhat like kerosene), which readily seizes plutonium, to concentrate the plutonium.

The normal process steps were to place the aqueous wash solution containing the plutonium and the organic solvent in a tank. Due to their different densities, the organic solvent would float on top of the aqueous solution. At this point the plutonium would still be dissolved in the aqueous solution, as shown in Figure 5-2a. When the aqueous solution is mixed by an agitator with the organic solvent, much of the plutonium will transfer from the aqueous solution to the organic solvent (see Figure 5-2b). Finally, when the agitator is turned off, the two solutions will separate, but now most of the plutonium will be in the organic solvent (see Figure 5-2c). The organic solvent, now containing most of the plutonium, would be transferred for further processing.

Figure 5-2a. 1958 - Los Alamos, Plutonium Dissolved in Aqueous Solution
Figure 5-2b. 1958 - Los Alamos, Plutonium Transferred to Organic Solvent
Figure 5-2c. 1958 - Los Alamos, Organic Solvent Separated from Aqueous Solution
Figure 5-2d. 1958 - Los Alamos, Stirrer Forced Aqueous Solution Upward Along the Outer Portion of the Organic Layer



The Accident

An unexpectedly large, plutonium-rich residue had built up in all the process vessels over many years of operation. For unknown reasons, the aqueous cleaning solution and its dissolved plutonium from at least two tanks were transferred into a large-diameter stainless steel tank. At some point before the nuclear criticality accident, organic solvents and aqueous solutions with low concentrations of plutonium had already been put into this large tank and that plutonium was already mainly in the organic solvent (much like Figure 5-2b). Up to this point, chemicals added to the mixed solutions kept them from separating, much as chemicals keep vinegar and oils from separating in salad dressings. After the addition of the aqueous solution from the two cleaned vessels, the balance was apparently upset. The organic solvent separated from the aqueous solution and floated to the top, with plutonium concentrated into the top layer much like the situation in Figure 5-2c. The concentration of the plutonium was just slightly below the critical concentration for that geometry.

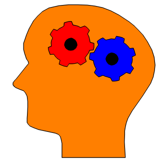
The operator turned on the stirrer to mix up the organic and aqueous solutions and looked into a sight glass to watch the operation. The initial action of the stirrer forced aqueous solution from the bottom of the tank upward along the wall, displacing the outer portion of the organic layer and thickening the central organic portion (see Figure 5-2d). This action changed the geometry of the organic plutonium solution from subcritical to critical. After an instant, the organic and aqueous solutions were remixed (see Figure 5-2a) and went subcritical because the plutonium, when spread throughout the entire liquid contents, was not concentrated enough to be critical. The solutions would remain subcritical unless two actions took place: (1) the solutions separated again after the stirrer was turned off, and (2) the stirrer was turned on again to create the same geometry as before.

The operator fell from the stepladder on which he was standing and stumbled out the door. A second chemical operator in an adjacent room saw a flash and went to help the first operator.

The nuclear criticality accident victim mumbled that he felt as though he was burning up. This led emergency response personnel to believe that there had been a chemical or plutonium exposure. Although most sources report that a radiation alarm about 40 meters away sounded, it was not determined for several minutes that a nuclear criticality accident had occurred.

Results

The nuclear criticality accident resulted in the death, 36 hours later, of the operator. His radiation dose was estimated to have been 12,000 rad. Two other people (one, the second operator mentioned above) suffered no apparent health effects after receiving doses of about 130 and 35 rad.



Activity 2 - Los Alamos Scientific Laboratory

Purpose: To identify the causes and termination mechanisms of the Los Alamos (1958) nuclear criticality accident.

Directions: Complete the questions. Answers are located in the answer key section of the Trainee Guide.

1. What were the events leading to this nuclear criticality accident?

2. What control factors are implied in this nuclear criticality accident?

3. What control factors were compromised and why?

4. What control factors shut down the nuclear criticality accident?

5. What preventative measures and/or lessons learned have occurred as a result of this nuclear criticality accident?

WOOD RIVER JUNCTION, RHODE ISLAND; JULY 24, 1964

Background

The only nuclear criticality accident at a commercial nuclear facility occurred July 24, 1964, in a plant located near Wood River Junction, Rhode Island.

The facility was designed to recover highly enriched uranium from unirradiated scrap material left from reactor fuel elements.

The plant at Wood River Junction was new, having started operations in March 1964. All normal process steps for this operation were covered by written procedures.

Criticality control was based on one or more limitations of volume, geometry, mass, or concentration of uranium solutions.

As expected with a new operation, the facility began experiencing problems with process equipment. One problem was in an evaporator used to concentrate uranium solution. The flow of solution through the evaporator had stopped because uranyl nitrate crystals had formed in a connection line. These crystals were dissolved with steam, which resulted in a concentrated enriched uranyl nitrate solution.

This solution was drained into several polyethylene, 5-inch-diameter, 11-liter bottles. These bottles had favorable geometry for these concentrated uranium solutions.

Another processing problem was that the solvent used in the separation columns was becoming more contaminated with uranium than expected, and large volumes of this solvent were being generated.

The concentration of uranium was too low to be critical at any volume.

The procedure for recovering the uranium from the solvent required adding sodium carbonate solution in a 5-inch-diameter, 11-liter bottle to the solvent. Then the bottles were manually shaken. The sodium carbonate solution bottles were identical to those holding the concentrated uranyl nitrate solutions.

The process of manually shaking the bottles was tedious. According to one account, an inventive worker who had the task of shaking the bottles knew the contaminated solvent was too diluted to produce a nuclear criticality accident. Therefore, he came up with a "better" method, which was pouring several bottles of solvent and sodium carbonate solution into a large tank with a power stirrer.

Two of the three shift supervisors were aware of this "better" method, but they were the only supervisors who knew, because the method had not been written down or approved. This "better" method violated the written procedure, which stated uranium solutions would not be put into large tanks.

The Accident

On the day of the nuclear criticality accident, one of the bottles of concentrated uranyl nitrate solution was apparently mistaken for contaminated solvent by a technician. This happened even though the bottle was labeled "Bottle Y - Concentrated Liquor from the Evaporator".

With the stirrer in motion, the technician poured one 11-liter bottle of concentrated enriched uranyl nitrate solution into the large tank, which already contained about 41 liters of sodium carbonate solution.

As the last of the uranyl nitrate solution entered the tank, the nuclear criticality accident occurred. (At this time, the solution's shape in the tank changed, and a critical excursion occurred. It probably looked similar to Figure 5-3a.)

The technician saw a blue-white flash and observed liquid splashing from the tank. Some of the solution reached the ceiling and some splashed on the technician.

The solution in the tank became subcritical at this point because approximately one-fifth of the liquid was splashed from the tank. The presence of air bubbles or a change in geometry (see Figure 5-3b) due to the action of the power stirrer may also have helped to cause the solution to become subcritical.

The nuclear criticality alarm sounded, and although the technician fell to the floor somewhat dazed, he remained conscious. He quickly got up, ran down three flights of stairs, and exited the building, retreating to a nearby emergency shack.

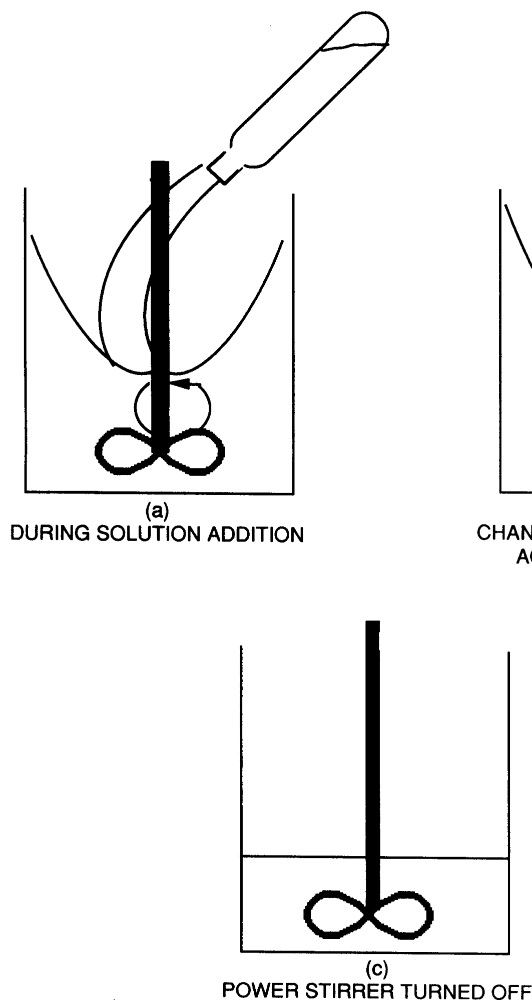
The technician was the only person exposed during the initial burst.

The plant superintendent and the shift supervisor entered the building several times following the nuclear criticality accident to survey for radiation and to shut down equipment. Little, if any, information was available about the first nuclear criticality when they reentered the building. Neither individual was wearing protective clothing or a respirator.

On the third entry, the superintendent turned off the power stirrer. With the power stirrer off, the geometry of the solution changed again (see Figure 5-3c), the bubbles disappeared, and a second, less violent burst occurred. This burst may have stopped because the uranium settled to the bottom of the tank.

The second nuclear criticality was not recognized by the two supervisors because the criticality alarm was still sounding from the first nuclear criticality accident.

Figure 5-3a. 1964 - Wood River Junction, Geometry During Solution Addition
Figure 5-3b. 1964 - Wood River Junction, Change in Geometry Due to Action of the Power Stirrer
Figure 5-3c. 1964 - Wood River Junction, Power Stirrer Turned Off



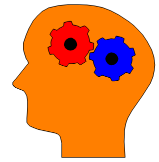
Results

The radiation dose received by the technician was estimated at 12,000 rad. The technician died 49 hours later.

The two supervisors received radiation doses of between 60 and 100 rad from the second nuclear criticality.

Other persons in the plant received very minor doses. No physical damage was done to the equipment, but cleanup of the splashed solution was required.

Activity 3 - Wood River Junction



Purpose: To identify the causes and termination mechanisms of the Wood River Junction (1964) nuclear criticality accident.

Directions: Complete the questions. Answers are located in the answer key section of the Trainee Guide.

1. What were the events leading to this nuclear criticality accident?

2. What control factors are implied in this nuclear criticality accident?

3. What control factors were compromised and why?

4. What control factors shut down the nuclear criticality accident?

5. What preventative measures and/or lessons learned have occurred as a result of this nuclear criticality accident?

You have completed this section.
Please check off your progress on the tracking form.
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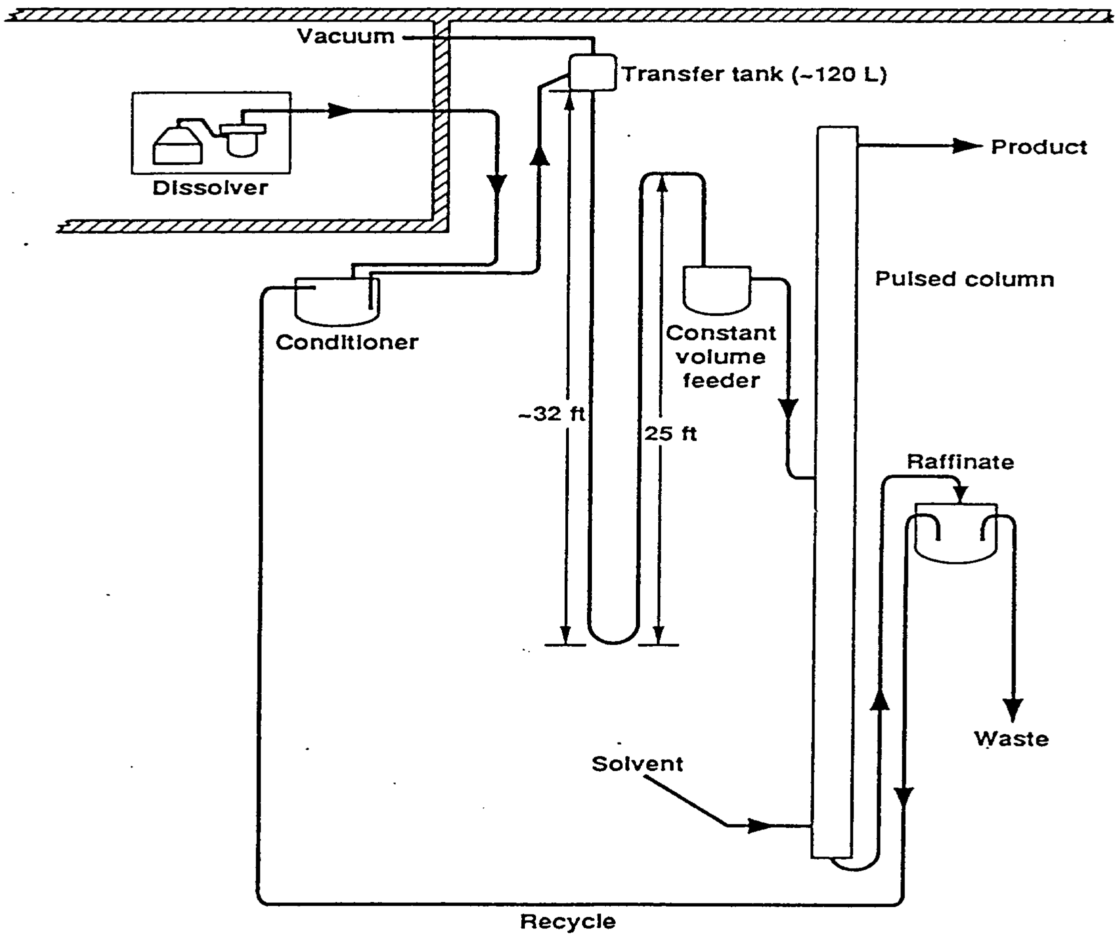
WINDSCALE WORKS, GREAT BRITAIN; AUGUST 24, 1970

Background

The Windscale Works plant was used to recover plutonium from miscellaneous scrap. Figure 5-4 displays the process line at the Windscale Works plant. The August 24, 1970, nuclear criticality accident occurred at the reactor fuel processing plant due to plutonium mass transfer from an aqueous nitric acid solution into 40 liters of organic solvent that had collected from an unknown source in an unfavorable geometry (61-cm diameter x 69-cm height) vessel.

Figure 5-4. 1970 - British Nuclear Fuels, Ltd., Process Line at Windscale Works



The British Nuclear Fuels, Ltd., process line at Windscale.

The Accident

The nuclear criticality accident occurred at the head end of a solvent extraction process that normally contained aqueous solution at a concentration of 6 g Pu/liter.

A transfer vessel containing this dilute aqueous solution collected 40 liters of organic solvent from an unknown source. The organic solvent floated like oil on water in the transfer vessel, which had a gravity drain in the bottom.

Due to the piping configuration (gravity drain) from the transfer vessel to the constant volume feeder, the floating solvent was unable to drain from the transfer vessel.

As each batch of aqueous solution flowed into the transfer vessel and through the organic solvent layer, the solvent continually extracted plutonium from the aqueous solution until the concentration had reached 55 g Pu/liter.

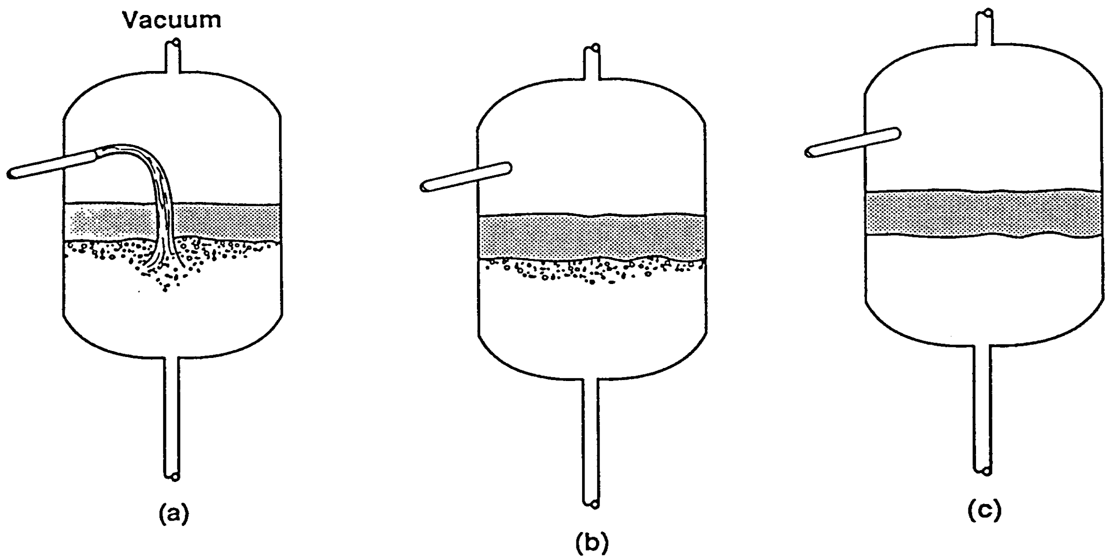
Each batch of 6 g Pu/liter aqueous solution flowing into the transfer tank created a momentary “hole” in the solvent layer (see Figure 5-5a), decreasing the system reactivity.

When the flow stopped (see Figure 5-5b), a transient aqueous-organic emulsion band formed (see Figure 5-5c), producing a more reactive system leading to the nuclear criticality accident of 1×10^{15} fissions.

Apparently, there was sufficient time between nitric acid washes for the plutonium concentration to increase until the system became slightly supercritical at the conclusion of a transfer, tripping the nuclear criticality alarms.

Radiation exposure was minimal due to the protection of the 1-foot-thick concrete shielding wall (two employees received less than 1 and 2 rads).

Figure 5-5a. 1970 - Windscale, “Hole” Created in Solvent Layer
Figure 5-5b. 1970 - Windscale, Solution Flow Stopped
Figure 5-5c. 1970 - Windscale, Emulsion Band Formed in Transfer Vessel

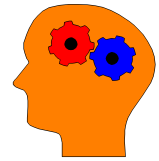


Results

Before operations were resumed four months later, neutron monitors were installed for detecting plutonium buildup in all vessels of unfavorable geometry.

Drain traps were also modified to ensure drainage and to facilitate washout procedures.

Activity 4 - Windscale Works



Purpose: To identify the causes and termination mechanisms of the Windscale Works (1970) nuclear criticality accident.

Directions: Complete the questions. Answers are located in the answer key section of the Trainee Guide.

1. What were the events leading to this nuclear criticality accident?

2. What control factors are implied in this nuclear criticality accident?

3. What control factors were compromised and why?

4. What control factors shut down the nuclear criticality accident?

5. What preventative measures and/or lessons learned have occurred as a result of this nuclear criticality accident?

You have completed this section.
Please check off your progress on the tracking form.
Go to the next section.

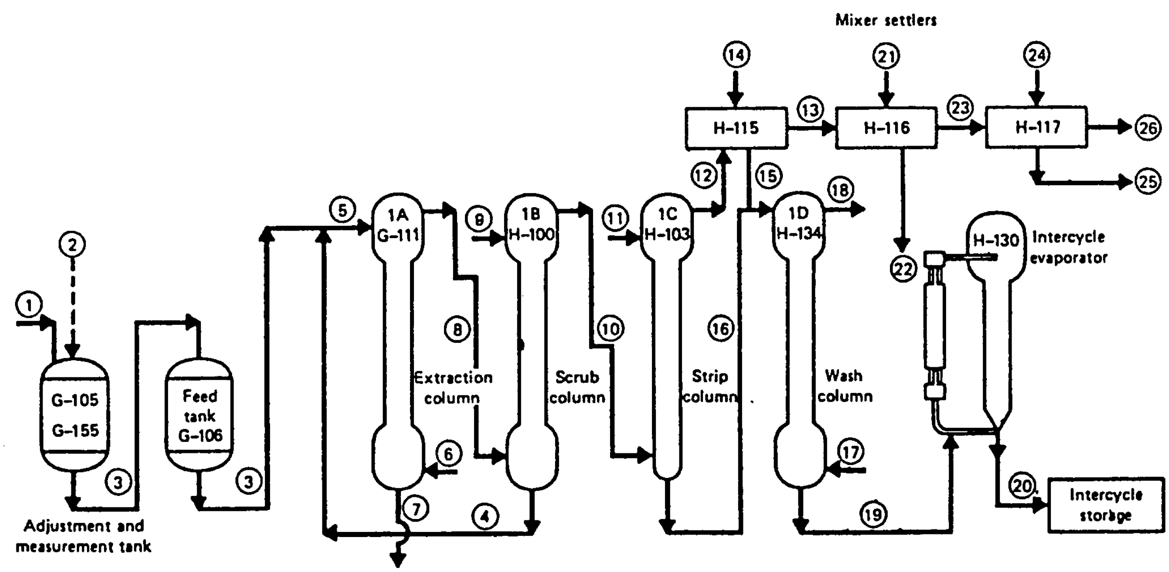
IDAHO CHEMICAL PROCESSING PLANT; OCTOBER 17, 1978

Background

The third nuclear criticality accident at the Idaho Chemical Processing Plant (ICPP) occurred on October 17, 1978, in continuous uranium solvent-extraction process equipment. (See Figure 5-6.)

Equipment breakdown, insufficient maintenance, and procedural breaches contributed to accidental enriched uranium solution accumulation in an unfavorable geometry section of a uranium extraction process scrub column.

Figure 5-6. 1978 -Idaho Chemical Processing Plant, First Solvent-Extraction Cycle



First solvent-extraction cycle for ICPP.

The Accident

Problems began when an evaporator plugged and uranium recovery operations had to be suspended for several weeks in order to correct instrumentation difficulties.

During the downtime, a leaking valve on a water supply line diluted the aluminum nitrate solution in a makeup tank (see Figure 5-7) used to make the feed for the H-100 scrub column.

The dilution in the makeup tank went unnoticed because the latest operating procedure, which required periodic sampling of the makeup tank, was not being used, and the density gauge, which would have indicated the dilution, had become inoperable.

The makeup tank was also equipped with a strip chart recorder to indicate the solution level in the tank, but the leak was so slow that the incremental level changes were not discernable without examining long lengths of chart covering several days. Also, the 3,000-liter process feed tank was supposed to have been equipped with a density gauge, but this had not been done.

Lastly, procedures required that a sample be obtained from the feed tank after each transfer from the makeup tank, but results of the analysis were not available until after the nuclear criticality accident had occurred.

In the scrubbing step of a continuous solvent-extraction process, uranium and other materials (fission products, in this case) in an organic solvent stream entered the bottom of a scrub column and flowed upward.

The aqueous scrubbing agent stream (aluminum nitrate solution, in this case) entered the top of the column and flowed downward. As the aqueous and organic streams mixed during their respective upward and downward flows, most of the uranium remained in the organic stream, which exited the top of the column.

The fission products, along with a small quantity of uranium, were scrubbed out into the aqueous stream, which exited the bottom of the column.

Control of the scrubbing agent concentration is the key factor in the process of removing fission products from the organic stream without removing significant quantities of uranium.

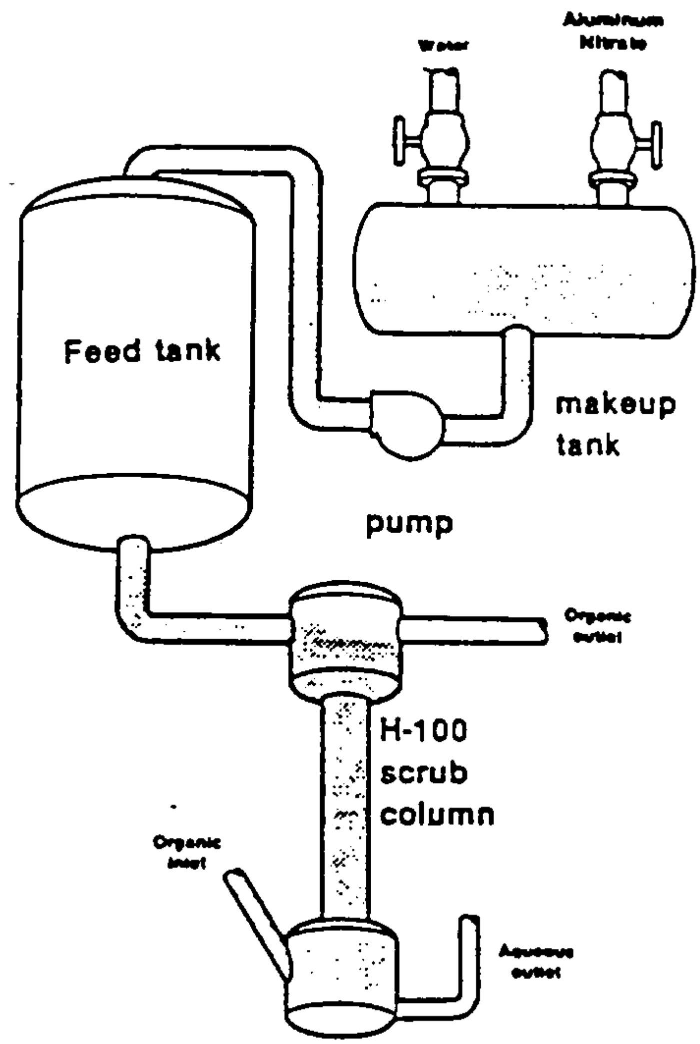
The aluminum nitrate solution was supposed to be maintained at 0.75 molar (about 160 g aluminum nitrate/liter) so the process would behave as described. Instead, due to the undetected water dilution in the makeup tank, the aluminum nitrate concentration was reduced to 0.08 molar (about 17 g aluminum nitrate/liter).
At this greatly reduced concentration, the scrubbing agent removed

more uranium from the organic stream, causing the uranium concentration in the unfavorable geometry bottom section of the scrub column to gradually increase from its usual 0.3 g U/liter to 22 g U/liter.

This increased concentration eventually achieved nuclear criticality, producing a total of approximately 2.7×10^{18} fissions.

The reaction was terminated by the increase in solution temperature due to the heat generated by the nuclear criticality and by partial shutdown of the extraction process by operating personnel as they evacuated.

Figure 5-7. 1978 - ICPP, Makeup Tank, Feed Tank, and H-100 Scrub Column



Results

Although heavy shielding in the area prevented any radiation exposure to personnel, the plant still suffered an extended and expensive shutdown.

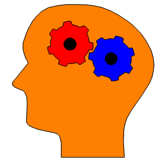
All operating procedures were reviewed in detail and revised where necessary.

Operator training was improved, and safety limits were reevaluated and developed into a technical specification format.

Redundant automatic safety controls and alarming instrumentation were developed and installed to monitor and provide response to abnormal process operation conditions.

The importance of maintenance of safety-related equipment and the need for adherence to well-developed operating procedures were reemphasized by this nuclear criticality accident.

Activity 5 - Idaho Chemical Processing Plant



Purpose: To identify the causes and termination mechanisms of the Idaho Chemical Processing Plant (1978) nuclear criticality accident

Directions: Complete the questions. Answers are located in the answer key section of the Trainee Guide.

1. What were the events leading to this nuclear criticality accident?

2. What control factors are implied in this nuclear criticality accident?

3. What control factors were compromised and why?

4. What control factors shut down the nuclear criticality accident?

5. What preventative measures and/or lessons learned have occurred as a result of this nuclear criticality accident?

You have completed this section.
Please check off your progress on the tracking form.
Go to the next section.

Self-Check Questions 5-1 ✔

Purpose: To identify the contributing factors of U.S. process plant nuclear criticality accidents.

Directions: Complete the table by placing an **X** for each contributing factor that is applicable to each facility incident. Answers are located in the answer key section of the Trainee Guide.

Contributing Factors	Y-12 1958	Los Alamos 1958	Wood River Junction 1964	Windscale Works 1970	Idaho 1978
Fissile Solution					
Inadequate or Not Chemically Analyzed/ Sampled					
Inadvertent Transfer of Solution					
Inventory in Process					
Misidentification of Material					
No Written Procedure					
Not Following Procedure					
Poor Communications in Operations					
Temporary Line					
Unfavorable Geometry Equipment					
Unusual or Irregular Operations					
Valve Leak					

(The following historical nuclear criticality accident summaries are excerpted from *A Review of Criticality Accidents Which Occurred in the Russian Industry*, written by V.V. Frolov, B.G. Ryazanov, and V.I. Sviridov for the State Scientific Center of Russian Federation, Institute of Physics and Power Engineering, G.S. Starodubtsev, Russian Federation, Enterprise “Mayak”.)

MAYAK ENTERPRISE, THE URALS; APRIL 21,1957

Background

Chamber for the purification of uranium solutions.

Equipment in a chamber for the purification of uranium solutions was designed for oxalate purification and the filtration of highly-enriched uranium. The chamber contained a process vessel with a 50-mm diameter and a capacity of 100 liters, equipped with a heater and a stirring device, a filter, a tank, and a vacuum trap on the solution outlet line.

No radiation monitoring devices were present in the chamber.

The staff operated, deviating from regulations: no regular cleanout of the equipment was performed, there were errors in accounting for uranium and other ingredients, the temperature of the process vessel was not monitored, and the condition of the filter was not checked. As a result of this, oxalate precipitate with a mass of 3.4 kilograms accumulated in the tank and a critical state was achieved for some time.

The Accident

On April 21, 1957, the operator noticed that the filter material was swelled and that the precipitate was discharging gases. This phenomenon was observed for a period of approximately 10 minutes. The reaction was terminated when part of the solution was forced from the tank into the trap.

Results

The operator died 12 days later. Five other workers developed radiation sickness.

The number of fissions, 2×10^{17}, was arrived at by averaging different estimates of what occurred.

MAYAK ENTERPRISE, THE URALS; JANUARY 2, 1958

Background

Critical parameters measurement facility for highly-enriched uranium solutions.

After two previous nuclear criticality accidents, an experimental facility for determining critical parameters in uranium solutions was installed at Mayak. The equipment included: a tank (”fixed to construction by bolt”), a neutron source and detectors, a control rod, and small diameter connecting lines.

The Accident

On January 2, 1958, after completing an experiment, a staff of four decided to speed the draining of a solution. They removed connecting bolts and placed some safe vessels nearby. Three people tipped the tank to drain the solution. At this point, the solution geometry became optimal, resulting in a power excursion.

In addition, due to proximity of the three people to the tank an effective neutron reflector was formed.

Results

A single spike of about 2.3×10^{17} fissions occurred. As a result, part of the solution was ejected from the tank.

Five to six days later, three of the four people died. The fourth person, who was 3 meters away, developed severe radiation sickness, resulting in a loss of eyesight.

This nuclear criticality accident, which had the most severe consequences, occurred because the staff was in serious violation of procedures. In addition, measures to assure nuclear criticality safety were insufficient.

The experimental facility for determining critical mass in uranium solutions was dismantled after this nuclear criticality accident.

SIBERIAN CHEMICAL COMBINE; AUGUST 14, 1961

Background

Facility for condensing and evaporating uranium hexafluoride. The facility was used for purifying uranium hexafluoride with an enrichment of 22.6%.

The line included the main cylinder, cooled by liquid nitrogen for condensing gaseous UF_6, additional vessels, a tank and a pump with a cylindrical 60-liter oil vessel. It was an experimental facility. The main cylinder lacked sufficient cooling, temperature control devices were not operational, and one of two additional vessels was bypassed.

The Accident

Because processing parameters were not observed, a portion of uranium hexafluoride passed through the pump and accumulated in the oil vessel. At the time of the nuclear criticality accident, the uranium concentration was about 400 grams per liter. The excursion yield was small - about 5×10^{15} fissions.

The alarm system was activated and the staff was evacuated. Measurements made with portable gamma-dosimeters did not confirm the occurrence of an nuclear criticality accident. A decision was made that it was a false alarm.

Results

Three hours, later the facility was started up again. This resulted in the occurrence of a second spike with the same number of fissions.

The operator received a radiation dose of 200 rad. At that moment, the operator was 0.5 meters away from the pump.

In both excursions, reactivity was compensated for by the increase in temperature and by some ejection of the oil. The total number of fissions was estimated to be 10^{16}.

The facility for purifying uranium hexafluoride was redesigned and reconstructed. Processing manuals and procedures were revised.

SIBERIAN CHEMICAL COMBINE; DECEMBER 13, 1963

Background

Facility for uranium extraction.

A vacuum control trap was installed behind the basic processing equipment on the main transfer line for uranium solution with high enrichment, small quantities of the extracting agent could be accidentally transferred into the trap. There were no records kept of the extracting agent used or lost in the process.

The Accident

The trap consisted of a vertical cylinder with a hemispherical bottom. Its diameter was 0.5 meters its volume, 100 liters. When the extracting agent was transferred into the trap, there was no way to observe or detect this event.

Periodically processing equipment up the line from the trap would overflow. As a result, the uranyl solution would accumulate in the trap and the extracting agent would gradually become saturated with uranium. When the nuclear criticality accident occurred, the trap was filled with a uranium solution concentration equal to 33 grams per liter.

The first power spike was small (1.6×10^{15} fissions), then, during the next six hours, a gamma radiation detector registered 16 oscillations with a decreasing intensity and periodicity.

Assuming that the reaction had shut down, a decision was made to switch off the vacuum system. As a result of this, part of the solution in the lines began to reenter the trap.

After an intense peak and subsequent power oscillations, the reaction reached a quasi-steady state. In order to stop the reaction, a cadmium solution was injected into the trap.

Results

A total of 2×10^{17} fissions was estimated to have occurred over 18 hours.

No one was injured. There were no personnel by the trap when the nuclear criticality accident began.

The alarm system was activated.

The staff was evacuated safely.

ELECTROSTAL FUEL FABRICATION PLANT; NOVEMBER 13, 1965

Background

Uranium dioxide powder unloading device. The process involved the conversion of uranium hexafluoride into uranium dioxide powder.

To improve the removal of powder from the conversion reactor, the receiving vessel was equipped with a vacuum system which included a line with two filters and a vacuum water pump.

The filters were checked rarely, and no NDA instruments for measuring uranium accumulation were used.

The Accident

On November 13, 1965, the alarm system was activated and the staff was evacuated. The investigation of the nuclear criticality accident showed that both filters were punctured and that the powder had accumulated in the water reservoir of the pump.

Slurry weighing 157 kilograms was extracted from the vessel which had a diameter of 300 mm and a height of 650 mm. The uranium had an enrichment of 6.5% and a mass of 51 kg.

Results

The number of fissions for one power spike equaled 10^{15}.

One worker received a dose of 3.5 rad.

The uranium dioxide power unloading device was dismantled.

OBSERVATIONS FROM SELECTED CRITICALITY ACCIDENTS

Russian Accidents

Analyses of the causes and consequences of these Russian nuclear criticality accidents provide the following observations:

1. Each of these nuclear criticality accidents occurred with hydrogen-moderated systems.

2. Two nuclear criticality accidents involved low enriched uranium (6.5% and 22%), the other involved systems containing highly enriched uranium.

3. In two instances, termination of the excursions resulted from external means.

4. No nuclear criticality accident resulted in damage to equipment. No unpredictable or inexplicable phenomena took place during the course of any of these accidents.

5. The major cause of the nuclear criticality accidents and/or the exacerbation of their consequences was human error and procedural violations by the staff.

6. Installation of safe equipment is the most reliable way to prevent nuclear criticality accidents.

7. In preventing nuclear criticality accidents, an important role is played by quantitative controls and by accurate accounting of both nuclear and chemical reagents.

8. Immediate evacuation of staff as soon as the alarm goes off provides an effective way to limit radiation exposure.

9. Accident mitigation measures should be undertaken only after the cause of the nuclear criticality accident is identified and reliable measures are in place to control the situation.

Activity 6 - Contributing Factors in Russian Criticalities

Purpose: To identify the contributing factors of Russian process plant nuclear criticality accidents.

Directions: Complete the table by placing an **X** for each contributing factor that is applicable to each facility incident. Answers are located in the answer key section of the Trainee Guide.

Contributing Factors	Mayak 1957	Mayak 1958	Siberian Chemical Combine 1961	Siberian Chemical Combine 1963	Electrostal' 1965
Design Flaws					
Fissile Solution					
Human Error					
Hydrogen-Moderated Systems					
Highly Enriched Uranium					
Low Enriched Uranium					
Lack of Monitoring					
Procedure Violations					
Termination Resulted from External Means					
Unfavorable Geometry Equipment					

The description below is from a report published in May 2000 by the Department of Energy's Los Alamos National Laboratory, titled, "A Review of Criticality Accidents," LA-13638, pp. 53-56.

JCO FUEL FABRICATION PLANT; SEPTEMBER 30, 1999

Background

The accident occurred in the Fuel Conversion Test Building at the JCO Fabrication Plant company site in Tokaimura, Ibarakin prefecture, Japan. The building housed equipment to produce either uranium dioxide powder or uranyl nitrate solution from source materials such as uranium hexafluoride or U_30_8 This building was one of three on site that was licensed to operate with fissile materials. The other two housed large-scale production equipment for the conversion of UF_6 to UO_2, for commercial light water reactors and handled only uranium enriched to 5% or less. The Fuel Conversion Test Building was much smaller, and was used only infrequently for special projects. It was authorized to handle uranium in enrichments up to 2O%.

At the time of the accident, U fuel processing (18.8 in a precipitation vessel) was underway, with the product intended for the Joyo experimental breeder reactor at the Oarai site of the Japan Nuclear Cycle Development Institute (JNC). The small size (300 x 500 meters) and inner-city location of the JCO Tokai site contributed to a unique aspect of this accident; this was the first process criticality accident in which measurable exposures occurred to off-site personnel (members of the public).

The operation required the preparation of about 16.8 kg of U(l8.8) as 370 g/l uranyl nitrate that was to be shipped, as solution, offsite for the subsequent manufacture of reactor fuel. The process was being performed in separate batches to comply with the criticality controls. Procedures specified different uranium mass limits for different enrichment ranges. For the 16 to 20% range the limit was 2.4 kg uranium. A simplified depiction of the main process equipment and material flow for preparing and packaging the uranyl nitrate, as specified in the license between the JCO Company and the federal government, is shown in Figure 5-8.

The Accident

Three operators had begun the task on 29 September, the day prior to the accident, but were operating according to the procedure indicated in part B of Figure 5-8. There were basically two deviations from the license-authorized procedure that were associated with the actual operations. First, the company procedure that the operators were to have followed specified that the dissolution step was to be conducted in open, 10-liter, stainless steel buckets instead of the dissolution vessel indicated. This change was known to have saved about one hour in dissolution time.

The much more serious procedural departure, however, was the transfer of the nitrate solution into the unfavorable geometry precipitation vessel instead of the prescribed, favorable geometry columns. This deviation was apparently motivated by the difficulty of filling the product containers from the storage columns. The drain cock below the columns was only about 10cm above the floor. The precipitation vessel had not only a stirrer to assure a uniform product but greatly facilitated the filling of the product containers.

On 29 September the operators completed the dissolution of four 2.4 kg batches. The solution was first transferred to a 5 liter flask and then hand-poured through a funnel into the precipitation vessel. The precipitation vessel was 450 mm diameter by 610 mm high with a capacity of about 100 liters. Figure 5-9 is a photograph of the actual precipitation vessel, interconnected piping, ports through which materials could be added, and the stairs on which one operator stood to pour the solution. The second operator stood on the floor and held the funnel. Completion of the four batches concluded the three-person team’s work for that day.

Figure 5-8. Authorized and Executed Procedures

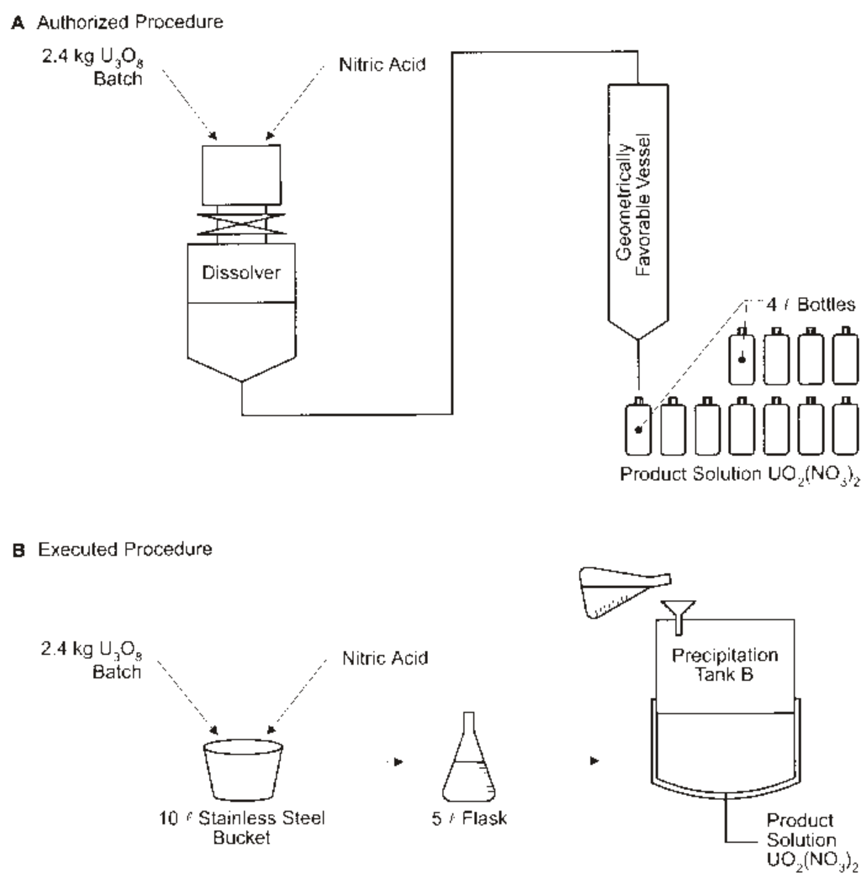
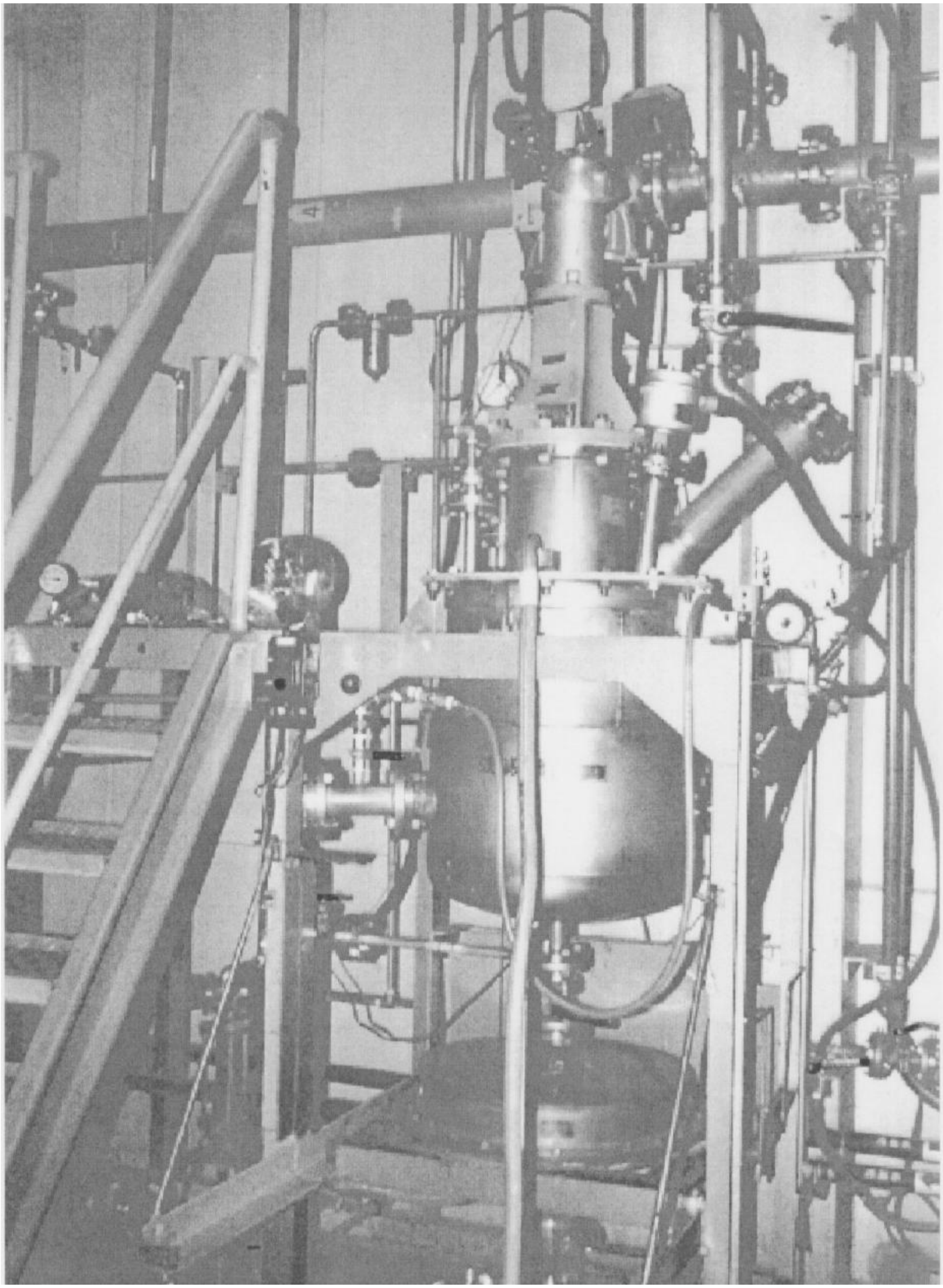


Figure 5-9. The Precipitation Vessel in which Process Criticality Accident Occurred



The next day, 30 September, the three operators began dissolving the final three batches that would be required to complete the job. After transferring batches five and six, the pouring of the seventh batch was begun around 10:35. Almost at the end of the pour (183 g of uranium were recovered from the flask) the gamma alarms sounded in this building and in the two nearby commercial fuel buildings. Workers evacuated from all buildings according to prescribed plans and proceeded to the muster area on site. At this location, gamma ray dose rates far above background were detected and it was suspected that a criticality accident had occurred and was ongoing.

The muster location was then moved to a more remote part of the plant site where dose rates were near to background values. The excursion continued for nearly twenty hours before it was terminated by deliberate actions authorized and directed by government officials. During this time there were several noteworthy aspects of this accident. First, the JCO Company was not prepared to respond to a criticality accident - the gamma alarms were not part of a criticality accident alarm system. In fact, the license agreement stated that a criticality accident was not a credible event. Thus expertise and neutron detectors had to be brought in from nearby nuclear facilities. Various monitoring devices at the facility as well as the nearby Japan Atomic Energy Research Institute (JAERI) recorded the excursion history. These showed, after a large initial spike, that the power level quasi-stabilized, dropping gradually by about a factor of two over the first ~17 hours.

About 4.5 hours after the start of the accident, radiation readings taken at the site boundary nearest to a residential house and a commercial establishment showed combined neutron and gamma ray dose rates of about 5 mSv/hour. At this time the Mayor of Tokaimura recommended that residents living within a 350 m radius of the JCO plant evacuate to more remote locations. After 12 hours, local Ibaraki-ken government authorities recommended that residents within a 10 km radius of the plant remain indoors because of measurable airborne fission product activity.

Shortly after midnight, plans were carried out to attempt to terminate the excursion. It was decided to drain the cooling water from the jacket surrounding the lower half of the precipitation vessel in the recognition that this might remove sufficient reactivity to cause subcriticality. Several teams of three operators each were sent, one at a time, to accomplish this job. The piping that fed the jacket was accessible from immedi ately outside the building, but it was difficult to disassemble and the workers were limited to exposures of less than 0.1 Sv each.

When the piping was finally opened at about 17 hours into the accident, not all the water drained from the jacket. This was determined from the various monitoring devices that showed a power drop of about a factor of four and then a leveling off again, indicating that the excursion was not terminated. Complete removal of the water from the jacket was eventually accomplished by forcing argon gas through the piping, again, without entering the building. This led to the shutdown of the reaction at about twenty hours. To assure permanent subcriticality, boric acid was added to the precipitation vessel through a long rubber hose.

Results

A few weeks after the accident, allowing for radiation levels to decay, the solution was sampled from the vessel and analyzed. Based on fission product analysis, it was determined that the total yield of the accident was about 2.5×10^{18} fissions. While there were no radiation detectors that recorded the details of the first few minutes of the excursion history, the operators' exposures and the neutron detector readings at the JAERI-NAKA site provide strong evidence that the reactivity exceeded prompt critical. Experimental results from simulated criticality accidents in solutions would then support a first spike yield of 4 to 8×10^{16} fissions.

The two workers involved in the actual pouring operation were severely overexposed, with estimated doses of 16 to 20 and 6 to 10 GyEq respectively. The third operator was a few meters away at a desk when the accident occurred and received an estimated I to 4.5 GyEq dose. All three operators were placed under special medical care. The operator standing on the floor holding the funnel at the time of the accident died 82 days later. The operator pouring the solution into the funnel died 210 days after the accident. The least exposed operator left the hospital almost three months after the accident.

Factors contributing to the accident, in addition to the stated procedural violations, likely included:

1) a weak understanding by personnel at all levels in JCO of the factors that influence criticality in a general sense, and specifically, a lack of realization that the 45 liters of solution, while far subcritical in the intended storage tanks, could be supercritical in the unfavorable geometry precipitation vessel;

2) company pressures to operate more efficiently;

3) the mind-set at all levels within JCO and the regulatory authority that a criticality accident was not a credible event; this mind-set resulted in an inadequate review of procedures, plans, equipment layout, human factors, etc. by both the company and the licensing officials.

The Government decided to cancel the license of JCO operations, and the JCO was likely to accept the decision at the time of the printing of this report.

Of the approximately 200 residents who were evacuated from within the 350 m radius, about 90% received doses less than 5 mSv and, of the remaining, none received more than 25 mSv. While there was measurable contamination from airborne fission products on local plant life, maximum readings were less than 0.01 mSv/hr and short-lived.

Self-Check Questions 5-2

Purpose: Identify the application of lessons learned from past criticality accidents.

Directions: List the design, management, and workplace practices (including those in the Standards) adopted from lesson learned through criticality accident histories for the following. Answers are located in the answer key section of the Trainee Guide.

1. Large, Unfavorable Geometry Containers	
2. Neutron Absorbers	
3. Administrative Procedures	

4. What factors contributed to most nuclear criticality accidents?

Directions: Read the following scenarios and list the similarities to previous nuclear criticality accidents.

Scenario A

A technician added 529 gallons of water to a tank over a time interval of 45 minutes in accordance with his interpretation of a handwritten instruction. The instruction read, “Add 500 gal water to tank...” An established plant nuclear criticality procedure includes the precaution, “To avoid an acid-deficient condition in tanks, do not add more than 200 gallons of water in any four-hour period.”

5. List the similarities to previous nuclear criticality accidents.

Scenario B

The event involved an inadvertent transfer of low-enriched uranium from a solvent exchange process to a waste treatment process at the General Electric (GE) Nuclear Fuel and Component Manufacturing Facility, located near Wilmington, North Carolina.

On the evening of May 28, 1991, a flow control valve failed to open. The valve was located between the solvent exchange process and the aqueous waste treatment process.

Concentrated low-enriched uranium was transferred from the solvent extraction process over a period of several hours as operators tried to control the symptoms without shutting the process down.

Approximately 150 kilograms of low-enriched uranium (3.2 weight percent ^{235}U) were inadvertently transferred from safe geometry process tanks through other tanks in a series of transfers to a nominal 20,000-gallon tank at the on-site waste treatment facility.

During the first hours of the event, operators did not fully realize what was happening and took inappropriate actions (including blocking the failed valve in the open position and failing to wait for the sample results to come back).

On May 29th, after receiving the first sample indicating a high uranium concentration, operators shut down the solvent exchange process.

The 150 kilograms transferred exceeded the safe mass limit for this waste tank (35 kilograms uranium at a maximum enrichment of 5 weight percent ^{235}U).

Water treatment chemicals already in this tank caused the uranium to precipitate out of solution, thus creating the potential for a nuclear criticality accident.

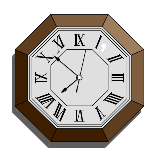
GE evacuated nonessential personnel from the area and removed the uranium precipitate from this tank via centrifuging operations over the next few days.

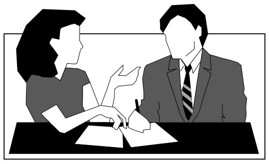
In a parallel effort, some of the uranium in this tank was transferred to other available tanks to reduce the mass in any one tank below the minimum critical value (approximately 100 kilograms uranium for 3.2 weight percent ^{235}U).

Note: Safe mass is nominally 45 percent of minimum critical mass.

6. List similarities to previous nuclear criticality accidents.

It's time to schedule a progress meeting with your administrator. Review the progress meeting form on the next page. In Part III, As a Regulator, write your specific questions to discuss with the administrator.





Progress Review Meeting Form

Date Scheduled:________________________________**Location:**______________________

I. The following suggested items should be discussed with the administrator as to how they pertain to your current position:

- Things that you can do to help prevent the recurrence of problems identified in previous nuclear criticality accidents.
- Ways to avoid a criticality accident.
- Process for implementing lessons learned from past criticality accidents.

II. Use the space below to take notes during your meeting.

III. As a Regulator:

- Confirm that lessons learned from incidents at the process/facility you are inspecting have been implemented.
- Confirm that generic lessons learned from events at other SNM facilities have been implemented in all plant areas.
- Confirm that operators are knowledgeable of and operating in accordance with approved operating procedures.
- Confirm that operators are controlling the inadvertent buildup of SNM.

IV. Further assignments? If yes, please note and complete. If no, initial completion of progress meeting on tracking form.

Ensure that you and your administrator have dated and initialed your progress on your tracking form for this module. Go to the module summary.

MODULE SUMMARY

Primary aspects of the historical nuclear criticality accidents presented in this module include:

- Events that Have Led to a Nuclear Criticality Accident
- Factors Affecting Nuclear Criticality
- Lesson Learned from Nuclear Criticality Accidents
- Preventative Measures that Resulted from Nuclear Criticality Accidents
- Similarities in Nuclear Criticality Accidents
- Ways to Avoid Nuclear Criticality Accidents

Accident descriptions of most, if not all, of the criticality accidents, including recent accidents and other not currently in Module 5.0, can be found in the Los Alamos National Laboratory Report, "A Review of Criticality Accidents", May 2000, LA-13638.

The following is a list of the process accidents taken from the report's Table of Contents:

- Mayak Production Association, 15 March 1953
- Mayak Producton Association, 21 April 1957
- Mayak Production Association, 2 January 1958
- Oak Ridge Y-12 Plant, 16 June 1958
- Los Alamos Scientific Laboratory, 30 December 1958
- Idaho Chemical Processing Plant, 16 October 1959
- Siberian Chemical Combine, 14 July 1961
- Hanford Works, 7 April 1962
- Mayak Production Association, 7 September 1962
- Siberian Chemical Combine, 30 January 1963
- Siberian Chemical Combine, 2 December 1963
- United Nuclear Fuels Recovery Plant, 24 July 1964
- Electrostal Machine Building Plant, 3 November 1965
- Mayak Production Association, 16 December 1965
- Mayak Production Association, 10 December 1968
- Windscale Works, 24 August 1970

- Idaho Chemical Processing Plant, 17 October 1978
- Siberian Chemical Combine, 13 December 1978
- Novosibirsk Chemical Concentration Plant, 15 May 1997
- JCO Fuel Fabrication Plant, 30 September 1999

Congratulations!

You have completed the final module of the Nuclear Criticality Safety Directed Self-Study Course. Go to the Directed Self-Study Course Process in the Trainee Guide. Ensure completion of all process steps.